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Optical spectroscopy of microquasar candidates at low galactic latitudes

J. Martí[1], J. M. Paredes[2,⋆], J. S. Bloom[3,4], J. Casares[5], M. Ribó[6], and E. E. Falco[7]

[1] Departamento de Física, Escuela Politécnica Superior, Universidad de Jaén, Virgen de la Cabeza 2, 23071 Jaén, Spain
e-mail: jmarti@ujaen.es
[2] Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, 08028 Barcelona, Spain
e-mail: jmparedes@ub.es
[3] Harvard Society of Fellows, 78 Mount Auburn Street, Cambridge, MA 02138, USA
[4] Harvard-Smithsonian Center for Astrophysics, MC 20, 60 Garden Street, Cambridge, MA 02138, USA
e-mail: jbloom@cfa.harvard.edu
[5] Instituto de Astrofísica de Canarias, Calle Vía Láctea s/n, 38200 La Laguna, Tenerife, Canary Islands, Spain
e-mail: jcv@ll.iac.es
[6] Service d'Astrophysique, CEA Saclay, Bât. 709, L'Orme des Merisiers, 91191 Gif-sur-Yvette, Cedex, France
e-mail: mribo@discovery.saclay.cea.fr
[7] Smithsonian Institution, F. L. Whipple Observatory, P.O. Box 97, 670 Mount Hopkins, Amado, AZ 85645, USA
e-mail: falco@cfa.harvard.edu

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Abstract. We report optical spectroscopic observations of a sample of 6 low-galactic latitude microquasar candidates selected by cross-identification of X-ray and radio point source catalogs for $|b^{II}| \leq 5^\circ$. Two objects resulted to be of clear extragalactic origin, as an obvious cosmologic redshift has been measured from their emission lines. For the rest, none exhibits a clear stellar-like spectrum as would be expected for genuine Galactic microquasars. Their featureless spectra are consistent with being extragalactic in origin although two of them could be also highly reddened stars. The apparent non-confirmation of our candidates suggests that the population of persistent microquasar systems in the Galaxy is more rare than previously believed. If none of them is galactic, the upper limit to the space density of new Cygnus X-3-like microquasars within 15 kpc would be $\lesssim 1.1 \times 10^{-12}$ pc^{-3}. A similar upper limit for new LS 5039-like systems within 4 kpc is estimated to be $\lesssim 5.6 \times 10^{-11}$ pc^{-3}.

Key words. X-rays: binaries – radio continuum: stars – quasars: emission lines

1. Introduction

Microquasars are X-ray binary systems with relativistic jets that behave as small scale replicas of quasars. The interest in such sources for high energy astrophysics has been reviewed by several authors (e.g., Mirabel & Rodríguez 1999). The reader is also referred to Castro-Tirado et al. (2001) and Durouchoux et al. (2002) for updated accounts of the recent findings. Microquasars provide excellent laboratories for the study of the physics of accretion/ejection phenomena and strong gravity, on time-scales more readily accessible to observers.

The number of confirmed microquasars currently known in the Galaxy is still relatively small: as of June 2002, only 14 objects were confirmed members with their jets being resolved (Ribó 2002). Their population includes systems as famous as Scorpius X-1 (the first extrasolar X-ray source discovered) and Cygnus X-1 (the first dynamic black hole candidate). The production of relativistic jets may be either persistent (e.g. Cygnus X-3, LS 5039, etc.) or transient (GRS 1915+105, V4641 Sgr, etc.). The relativistic ejecta have been observed to move at apparent superluminal speeds in a few systems. Moreover, both high and low-mass X-ray binaries have been found to behave as microquasars. In this context, the rather heterogeneous properties of microquasars as a group make it difficult to derive statistically robust results. In this respect, the discovery of new sources is required to drive a deeper understanding of the phenomema.

We searched for new microquasar systems in the Galaxy by cross-identification techniques between X-ray and radio catalogs, namely the ROSAT all sky Bright Source Catalog (RBSC, Voges et al. 1999) and the NRAO VLA Sky Survey (NVSS, Condon et al. 1998). The selection criteria and the list of candidates have been described extensively in Paredes, Ribó & Martí (2002), hereafter PRM02, where the search was initially

Send offprint requests to: J. Martí,
e-mail: jmarti@ujaen.es
⋆ CER on Astrophysics, Particle Physics and Cosmology. Universitat de Barcelona

Table 1. Log of the spectra for the high priority targets observed.

1RXS Source	Date 2002	Gratings used at the WHT	Integration time (s)
J001442.2+580201	Dec 3	R316R, R300B	3×2000
J013106.4+612035	Dec 8	R158R, R300B	1×1800
J042201.0+485610	Dec 8	”	”
J062148.1+174736	Dec 2	R316R, R300B	2×2000
J072259.5−073131	Dec 2	”	2×2000
J072418.3−071508	Dec 8	R158R, R300B	1×1800

limited at low galactic latitudes $|b^{II}| \leq 5°$. In this paper we present optical spectroscopy for six of the priority targets reported in PRM02, which were also observed with the EVN and MERLIN by Ribó et al. (2002a). These spectroscopic observations provide a crucial test to discern whether a candidate is actually of stellar nature, as expected for a microquasar, or an extragalactic object. For genuine microquasars, we expect to detect either emission lines or absorption features of stellar photospheric origin, both with a relatively small Doppler shift due to an eventual radial velocity of the optical companion. Alternatively, the detection of any emission or absorption features with a clear cosmological redshift would indicate an extragalactic source (a quasar or other AGN).

As described herein, most of our candidates turned out to have featureless continua; no new microquasar has been positively confirmed so far. Additional observations are still necessary before the spectroscopic study of the full sample is completed. Nevertheless, the negative results to date would suggest that persistent microquasars are not a prolific nor long-lived state of Galactic binaries.

2. Observations

The spectroscopic observations were carried out with the 4.2 m William Herschel Telescope (WHT) at the Roque de los Muchachos observatory in Canary Islands (Spain) in both visitor and service mode. The ISIS double-armed spectrograph was used with different gratings in the red and blue arms, for a resolution of 5 to 10 Å. The technical details of this instrument are described in the ISIS manual (Carter et al. 1994). The main observations of this paper were conducted in 2002 December 2, 3, 4 and 8, with the last night being in service mode. The observing log is listed in Table 1, which contains the source name, the observation date, the ISIS grating used and the integration time.

Further WHT data were also obtained on 2002 January 24, February 3 and 2003 January 21 for preliminary or verification purposes. Additional data were also taken with the 6.5 m Multiple Mirror Telescope (MMT) and its spectrograph in Mount Hopkins (Arizona, USA). On the MMT, we used the Blue Channel Spectrograph with a 300 gpm grating and a $2 \times 180''$ slit, for a resolution of about 6.2 Å. The spectra covered about 4800 Å, centered on 5900 Å, and the 3072×1024-pixel ccd22 was used as a detector.

For each target, we obtained a series of two or three WHT spectra, with exposure times of 1800–2000 s, with the idea of combining them during the reduction process. The wavelength calibration was performed using arc frames taken with Copper-Neon & Copper-Argon lamps at the same telescope position of the target. Arc frames were obtained before and after the science frames. A wide range of air masses, atmospheric transparency and seing conditions was experienced on the different nights. A similar strategy was followed at the MMT, where we acquired the data at airmass $\sim$1.3 with seeing of about $1.5''$, under photometric conditions. For each target, we obtained 2×1800 s integrations; we used Helium-Neon-Argon calibration lamps before and after each exposure.

The data reduction was carried out using the IRAF package of NOAO including bias subtraction, spectroscopic flat fielding, optimal extraction of the spectra and interpolation of the wavelength solution. A few spectroscopic standards were also observed and used to remove the spectral response and to flux-calibrate the data. Unfortunately, the non-photometric conditions on several nights precluded a good absolute calibration and this is most likely accurate only within $\pm$0.3 magnitudes in some spectra.

The extracted spectra are presented in Figs. 1 to 6. The discussion for each individual target is given in the following section. The blue arm data of ISIS have not been included in some spectral plots due to problems in connecting the red and blue flux calibrated data. This occurred specially on 2002 December 2 due to bad sky transparency conditions, thus resulting in a higher extinction at shorter wavelengths.

3. Results on individual sources

Due to visibility constraints when our WHT observing time was allocated, only the sources with Right Ascension in the 0–8 h range could be observed, i.e., those that were also observed with the VLA in our original paper and with the EVN and MERLIN in Ribó et al. (2002a).

3.1. 1RXS J001442.2+580201

This is the weakest optical source in our sample with $I \simeq 20$ mag. 1RXS J001442.2+580201 was originally considered to be a promising candidate because of its two-sided relativistic radio jets (with $\beta > 0.2$) detected in the EVN observations by Ribó et al. (2002a), as well as possible evidence of radio proper motion of the core close to the 3σ level. However, its optical spectrum in Fig. 1 failed to reveal clear emission lines or stellar photospheric features. This statement applies to both the WHT and MMT spectra plotted in this figure. A simple continuum with a possible interstellar and other atmospheric absorptions is detected instead. The nature of this target remains still unknown although a galactic stellar origin seems to be ruled out unless it is a strongly reddened star (see discussion in Sect. 4.1). A second epoch of WHT observation, obtained in service mode in 2003 January 21, confirmed the featureless spectrum of this object at a comparable emission level.

Interestingly, the MMT spectrum of 1RXS J001442.2+580201 taken on 2002 October 6 clearly in-

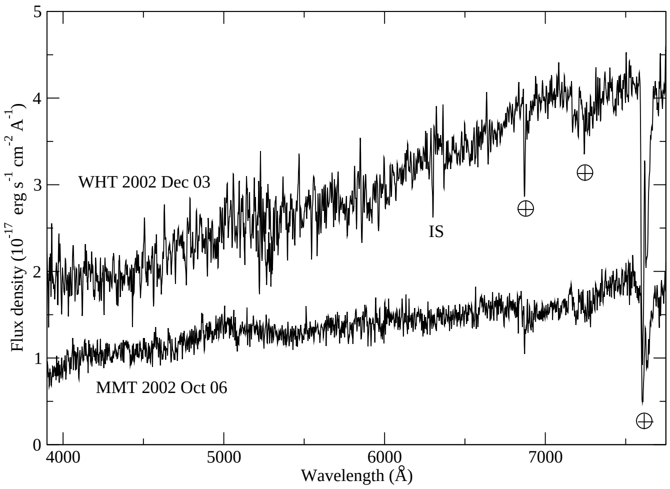

Fig. 1. Optical spectra of 1RXS J001442.2+580201 taken on different epochs with the WHT and the MMT. Both spectra display a simple continuum without obviously identifiable features. A possible interstellar (IS) absorption line is indicated as well atmospheric absorption bands. Such last features are more obvious in the WHT spectrum when the source was apparently brighter.

dicates that the brightness of the source was significantly fainter by a factor of ∼2. The reality of this variability, on time scales of months, could be affected by possible slit losses and other absolute calibration uncertainties. However, if confirmed, such variations would not be unusual for an extragalactic source.

3.2. 1RXS J013106.4+612035

This source was observed to exhibit a relativistic one-sided radio jet in the EVN maps (with $\beta > 0.3$). Possible proper motion of the core at the 4σ level was also reported, although Ribó et al. (2002a) were very cautious about this claim. Its spectrum in Fig. 2 taken in service mode displays a featureless continuum heavily absorbed at shorter wavelengths. Only interstellar and atmospheric absorption features are detected. An MMT spectrum is also consistent with these statements, but we do not show it here due to likely contamination by a nearby star in the slit already present in optical images (see Fig. 2 of PRM02). The one-sided jet and the featureless continuum point to a possible blazar interpretation for 1RXS J013106.4+612035. Thus, a stellar origin does not seem appropriate for this source which is most likely extragalactic. Nevertheless, a highly reddened star cannot be completely excluded as in the previous case. The equivalent width (about 0.9 Å) of the Na I interstellar feature (5890.0–5895.9 Å), well visible for this source, does point toward a high extinction value according to the Munari & Zwitter (1997) calibration ($A_V \geq 4.5$ mag).

3.3. 1RXS J042201.0+485610

The spectrum of this source in Fig. 3 clearly shows strong emission lines that we identify as redshifted Hα+[N II], [O III] and

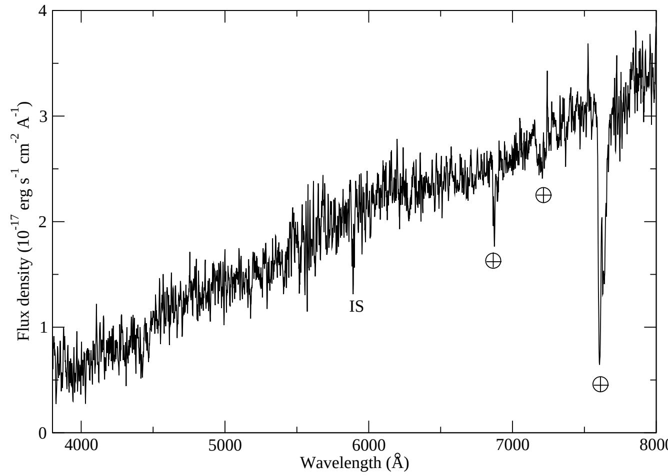

Fig. 2. Optical spectrum of 1RXS J013106.4+612035.

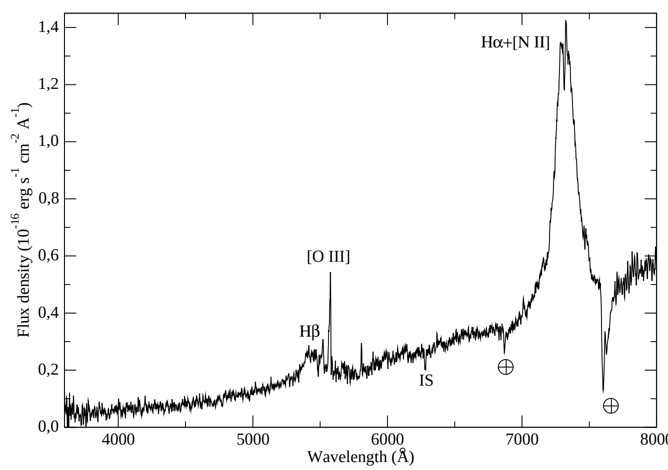

Fig. 3. Optical spectrum of 1RXS J042201.0+485610 with broad emission lines of hydrogen suggesting that it is a Seyfert 1 galaxy.

Hβ. The Hα+[N II] blend has a broad Full Width Zero Intensity of ∼20 000 km s^{-1}. Using all identified lines, the redshift is consistently estimated to be $z = 0.114 \pm 0.002$. An extragalactic origin is therefore confirmed. This was already suspected in PRM02 given the Full Width Half Maximum (FWHM) ∼15% greater than point like sources in optical images. The broadness of the hydrogen lines suggests that this is a likely Seyfert 1 galaxy seen through the Galactic Plane. The observed spectrum is actually very similar to that of the Seyfert 1 galaxy and hard X-ray source GRS 1734−292 behind the Galactic Center (Martí et al. 1998).

3.4. 1RXS J062148.1+174736

This source does not have any remarkable feature in the spectrum shown in Fig. 4 excluding atmospheric and weak interstellar absorptions. Such featureless continuum suggests a non-stellar origin and hence 1RXS J062148.1+174736 is likely an extragalactic object. This was already indicated by a FWHM ∼30% larger than point-like objects in the optical images by

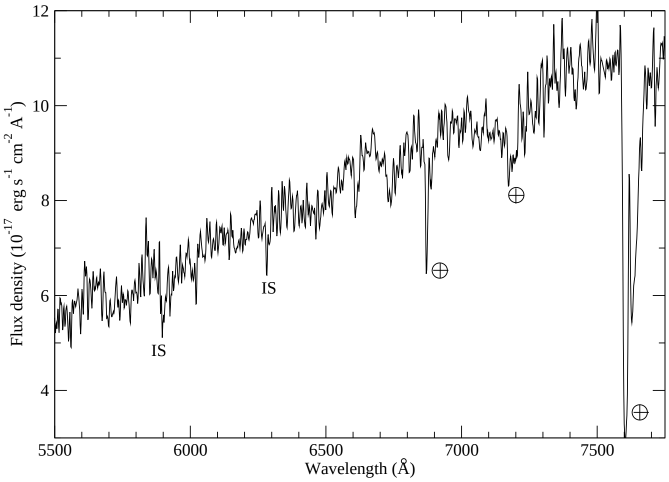

Fig. 4. Optical spectrum of 1RXS J062148.1+174736. It cannot be ruled out that the apparent wiggles in this spectrum result from a sky subtraction artifact.

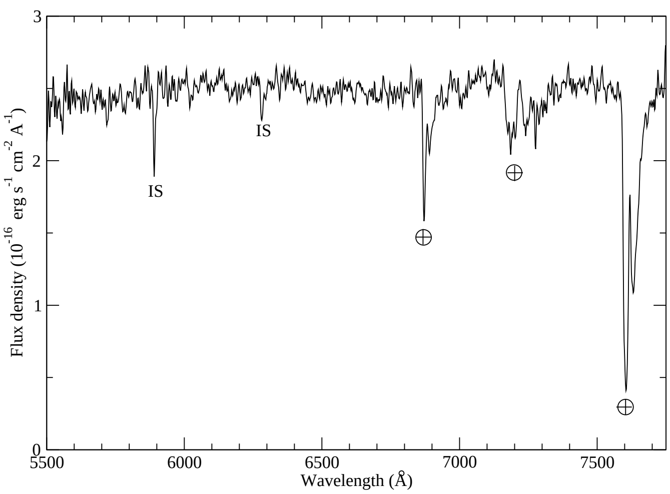

Fig. 5. Optical spectrum of 1RXS J072259.5−073131. This object, at a galactic latitude of 3.5°, appears to be unusually blue. The uncertain flux calibration for the night when it was taken (Dec 2) may have affected however the slope of the continuum.

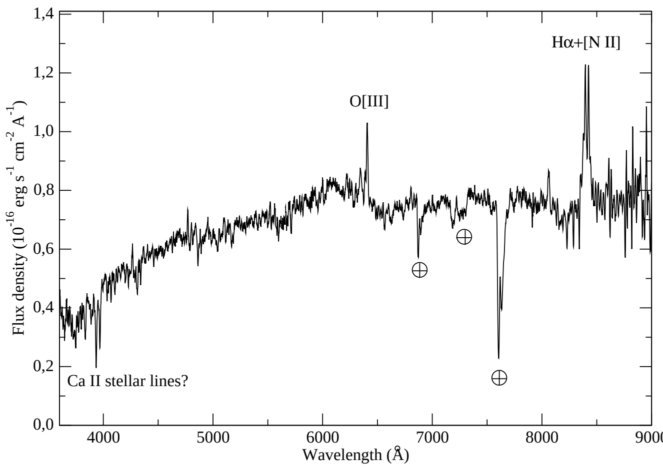

Fig. 6. Optical spectrum of the flat spectrum radio quasar 1RXS J072418.3−071508. The Ca II absorption lines are likely to be due to a superposed late type star.

PRM02 thus excluding possible reddening effects on a stellar continuum.

3.5. 1RXS J072259.5−073131

A relativistic one-sided radio jet (with $\beta > 0.3$) has been detected from this source at both arcsecond (PRM02) and subarcsecond scales (Ribó et al. 2002a). The bending of the jet in the EVN maps was reminiscent of the ones seen in blazar sources. The featureless continuum typical of blazars that appears in the optical spectrum of Fig. 5 is also in agreement with this interpretation. 1RXS J072259.5−073131 is therefore a likely extragalactic source. The possiblity of a stellar reddened continuum does not seem likely as the object appears significantly blue.

3.6. 1RXS J072418.3–071508

This source was considered a candidate when we first performed VLA and optical observations at the early stages of our research. However, around this epoch the source was classified as a flat spectrum radio quasar by Perlman et al. (1998) with a redshift of $z = 0.270$. Our spectrum in Fig. 6 shows the presence of strong, redshifted emission lines of Hα+[N II] and [O III] for this relativistic one-sided radio jet source with $\beta > 0.5$ (Ribó et al. 2002a). We derive a redshift estimate of $z = 0.280 \pm 0.001$, not very different from the previous finding. The small discrepancy is probably due to the different signal-to-noise ratio between our spectrum and that of Perlman et al. (1998). Hα+[N II] were noticeably stronger at the epoch of our observations. The presence of Ca II absorption lines close to their rest wavelength in Fig. 6 could be explained if a late type star is almost superposed on the quasar line of sight. The presence of this star is inferred from the double appearance of this source in CCD optical images (see Fig. 2 of PRM02).

4. Discussion

The selection of microquasar candidates by PRM02 was mostly sensitive to persistent systems, especially in high mass X-ray binaries (HMXBs). Indeed, the selection algorithm recovered well known microquasars such as SS 433, Cygnus X-3 and LS 5039, as well as the Be HMXB LS I +61 303 (also a source of relativistic jets as observed with the EVN and MERLIN; Massi et al. 2001; Massi et al. 2003). The selection algorithm did not recover any low mass X-ray binary (LMXB). This can be understood because LMXBs tend to be transient sources at both X-ray and radio wavelengths, hence not being generally present in the NVSS nor the RBSC.

Unfortunately, however, none of the six priority candidates in PRM02 appears to be clearly of galactic stellar nature. One of them is a Seyfert galaxy and another a significantly redshifted quasar. The other four exhibit a featureless continuum with only interestellar absorption lines superimposed on it, reminiscent of BL Lac objects or blazars. Such extragalactic

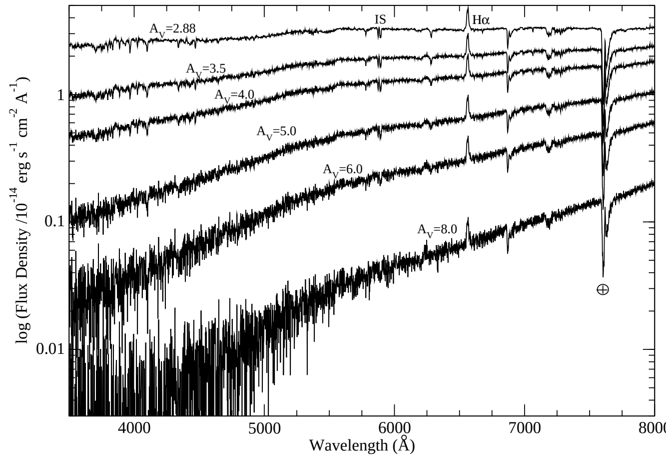

Fig. 7. Optical spectra of the microquasar LS I +61 303 as would be observed with increasing values of the extinction at optical wavelengths assuming constant exposure time. The 120 s spectrum at the top of the plot was originally taken with the WHT and ISIS on 2002 December 2 ($A_{\rm V} = 2.88$). Logarithmic vertical scale is used to better illustrate how the photospheric lines of the stellar companion become progressively difficult to detect within noise as the extinction and reddening increase. Only the strong Hα emission line of the system would eventually remain as a conspicuous feature.

interpretation seems more likely for 1RXS J062148.1+174736 and 1RXS J072259.5−073131, whose spectra have a relatively good signal-to-noise ratios (SNR) of about 30 and 50, respectively. Indeed, at this SNR, a stellar spectrum should normally be recognizable and even a stellar spectral type derived. This is clearly not the case for these two objects.

Nevertheless, it could still be possible that the remaining two featureless sources are highly reddened stars seen through the disc of the Galaxy, as already advanced in the previous section. This statement applies to 1RXS J001442.2+580201 and 1RXS J013106.4+612035 whose observed spectra are of poorer quality.

4.1. Highly reddened stars?

In order to consider the possibility just quoted above, we have carried out the exercise of reddening the optical spectrum of a HMXB microquasar such as LS I +61 303 in a progressive way. The intrinsic reddening towards this system is assumed to be $E(B-V) = 0.93$ mag, equivalent to a visual extinction of $A_V = 2.88$ mag (Hutchings & Crampton 1981). The IRAF task DEREDDEN was used for this purpose. The original spectrum of LS I +61 303 was taken using the WHT with the same instrumental setup as for our candidate sources. In Fig. 7, we display the different spectra of this microquasar as seen with increasing values of extinction. Noise was artificially added with the IRAF task MKNOISE to approximately simulate the decaying SNR expected while the flux density decreases progressively with reddening. Exposure time is assumed to remain constant. It is clear from this plot that the many photospheric lines of the early type star become less and less evident as A_V increases, specially in the blue part of the spectrum. The most reddened spectra in Fig. 7 have a SNR∼10 in this region, i.e., comparable to that of 1RXS J001442.2+580201 and 1RXS J013106.4+612035 in our real observed spectra. Therefore, we cannot strictly rule out the possibility of highly reddened stars in addition to the BL Lac interpretation for these two featureless sources. Addtional spectroscopic observations, with higher SNR (or at infrared wavelenghts), would be necessary to distinguish between the two interpretations.

4.2. The extragalactic alternative

If the ambiguous sources are not highly reddened stars, then all our candidates would turn out to be extragalactic sources and no new microquasar would be present among them. Although some secondary candidates remain to be explored, a non-detection of new microquasars is nevertheless noteworthy.

Assuming that all our sources are extragalactic, it is possible to estimate an upper limit for the density of new persistent microquasar systems in the Galaxy. In order to do so, we need to assess the galactic regions accessible to our search as follows. The NVSS and the RBSC come from surveys obtained in different epochs separated by few years. Hence, a microquasar is most likely to be present in both of them in case it is a persistent source over the years. The NVSS was conducted at the 20 cm wavelength with the VLA and its brightness limit is such that sources with flux density of ∼2.5 mJy are the weakest reliable detections.

The RBSC was compiled using PSPC data from the ROSAT satellite, in the energy range 0.1–2.4 keV, and its brightness limit is about 0.1 count s^{-1}. This limit corresponds to an unabsorbed energy flux that depends on the source spectrum and the amount of hydrogen column density $N_{\rm H}$ towards it. The column density can be estimated using the Predehl & Schmitt (1995) relationship with the extinction at visual wavelengths A_V. We will further assume a crude but plausible value of 1.9 mag kpc^{-1} for the total absorption of star light near the galactic plane (Allen 1973), that is:

$$N_{\rm H} = 1.79 \times 10^{21}\ {\rm cm}^{-2} A_V = 3.40 \times 10^{21} D\ {\rm cm}^{-2} \quad (1)$$

where D is the distance to the source in kpc.

A persistent microquasar like Cygnus X-3 typically has a 20 cm flux density of ∼100 mJy at about 10 kpc from the Sun. Therefore, it would be detected in the NVSS up to a distance $\leq$ 63 kpc since the Galaxy is almost transparent at cm wavelengths. The situation is more restrictive in the ROSAT energy range. Here, the plausible persistent X-ray luminosity of a Cygnus X-3 system would be $L_{\rm X} \sim 10^{37}$ erg s^{-1} and we will further assume a power law index $\Gamma = +2$. For such object to appear detected in the RBSC above the 0.1 count s^{-1} level, its distance needs to be $\leq$ 15 kpc. This number has been derived using the web based tool PIMMSv3.3d originally developed by Mukai (1993) for flux and count conversion between different X-ray observatories. To do so, from Eq. 1, the plausible hydrogen column density at 15 kpc is crudely estimated as $N_{\rm H} = 5.1 \times 10^{22}$ cm^{-2}. Then, the unabsorbed energy flux corresponding to 0.1 count s^{-1} according to PIMMSv3.3d is

4.2×10^{-10} erg cm^{-2} s^{-1}, which is consistent with the assumed X-ray luminosity when multiplied by $4\pi D^2$.

By imposing a detection at both radio and X-rays, the microquasar search using the PRM02 criteria is sensitive to Cygnus X-3 like systems within the second (smaller) distance limit of $D = 15$ kpc. This includes a substantial volume of the Galaxy, which can be estimated as:

$$V = \frac{4\pi}{3} \eta D^3 \sin |b^{II}|_{\max}, \tag{2}$$

where η is the fraction of the Galactic Plane sampled in our search and $|b^{II}|_{\max} = 5°$ its limit in galactic latitude. The fraction η is set mainly by the declination limit ($\delta \geq -40°$) in PRM02, which only allowed to search within galactic logitudes $-13.3° \leq l^{II} \leq 259.2°$. This represents 75.7% of the Galactic Plane. However, our search close to the Galactic Center (roughly $-1° \leq l^{II} \leq 1°$) is severely affected by source confusion specially in the NVSS. This reduces the sampled fraction by 0.55% only, but it is very likely that many interesting sources have been missed in these central regions of the Galaxy. Excluding this caution, we have $\eta \simeq 0.75$ and consequently $V \simeq 920$ kpc^3. The fact that not even one Cygnus X-3-like system has been apparently discovered suggests that bright (and persistent) microquasars are probably not very abundant in the galactic disc. The corresponding upper limit for new Cygnus X-3 systems ($\leq 1/V$) is about $\lesssim 1.1 \times 10^{-12}$ pc^{-3}.

There is, of course, the alternative of a persistent but fainter microquasar population which could have been missed by our search. In this case, how far away could we detect such systems? Let us assume that these objects are comparable to LS 5039, which is a relatively faint system at both X-ray ($L_X \sim 5 \times 10^{34}$ erg s^{-1}) and radio (~20 mJy at 20 cm) wavelengths at 2.9 ± 0.3 kpc from the Sun (Paredes et al. 2000, Ribó et al. 1999, 2002b).

Under such assumptions, and proceeding just as above, such faint and persistent microquasars would be detected in the NVSS for distances ≤ 8.5 kpc and in the RBSC for distances $\leq$ 4 kpc. A simultaneous detection, in both surveys, would be thus possible only for relatively nearby systems within $D = 4$ kpc from the Sun. Again, no new system of this kind has been apparently discovered in our search. If they exist, their population in the vicinity of the Sun does not seem to be very numerous as well, at least close to the galactic plane. Using again Eq. 2 we have a sampled volume of $V \simeq 18$ kpc^3 in this case, with the corresponding density upper limit for new LS 5039-like systems being $\lesssim 5.6 \times 10^{-11}$ pc^{-3}.

However, there may be several faint and persistent microquasars at larger distances in the Galaxy where our search is not sensitive to them. On the other hand, it may also well happen that nearby systems are naturally located at galactic latitudes higher than what we have been searching for and a more extended search is then necessary. Similarly, higher galactic latitudes for LS 5039-like systems appear also conceivable as they may be runaway microquasars escaping from the galactic disc (Ribó et al. 2002b).

In this context, we have just started to expand our cross-identification studies to $5° \leq |b^{II}| \leq 10°$. This is not a simple task considering the increasing amount of sky to be covered, which provides a large number of sources to be explored. Results from this expanded search will be reported in other papers. Future searches would also benefit from sensitive surveys in gamma and hard X-rays, such as the current INTEGRAL Galactic Plane Survey and the planned EXIST mission.

5. Conclusions

1. Spectroscopic observations have been reported for six of the high priority microquasar candidates reported in PRM02 within galactic latitude $|b^{II}| \leq 5°$. Two of them are clearly extragalactic objects while the remaining four display a featureless continuum in their spectra.
2. The four candidates with featureless spectra are reminiscent of BL Lac or blazars and would be therefore extragalactic sources as well. However, the possibility that two of them (1RXS J001442.2+580201 and 1RXS J013106.4+612035) are highly reddened stellar systems cannot be completely excluded based on the present data.
3. Assuming that none of our candidates is galactic, it appears that the population of new and persistent microquasars is not very numerous in the Galaxy. The corresponding density of new Cygnus X-3 and LS 3039-like system is constrained to be $\lesssim 1.1 \times 10^{-12}$ pc^{-3} and $\lesssim 5.6 \times 10^{-11}$ pc^{-3}, respectively.

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